Formation of Large-Scale Obscuring Wall and AGN Evolution Regulated by Circumnuclear Starbursts

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ABSTRACT

By considering the radiative force by a circumnuclear starburst as well as an AGN, we analyze the equilibrium configuration and the stability of dusty gas in the circumnuclear regions. It is found that the radiative force by an intensive starburst can support a stable gaseous wall with a scale-height of several hundred parsecs. Moreover, by taking the simple stellar evolution in the starburst into account, we find that the covering factor of the wall decreases on a time-scale of several 10^7 yr. The large-scale wall, if formed, works to obscure the nucleus due to the dust opacity. Hence, it is anticipated that the index of AGN type tends to shift from higher to lower in several 10^7 yr according as the circumnuclear starburst becomes dimmer. On the other hand, if the AGN itself is brighter than the circumnuclear starburst (e.g. quasar case), no stable large-scale wall forms. In that case, the AGN is highly probably identified as type 1. The present mechanism may provide a physical explanation for the putative correlation between AGN type and host properties that Sy2's are more frequently associated with circumnuclear starbursts than Sy1's, whereas quasars are mostly observed as type 1 regardless of star-forming activity in the host galaxies.

Subject headings: galaxies: active — galaxies: evolution — galaxies: nuclei — galaxies: starburst — quasars: general — radiative transfer

1. Introduction

Recently, intriguing evidences regarding the host galaxies of active galactic nuclei (AGNs) and quasars (QSOs) have been accumulated. First, it has been reported that host galaxies of Seyferts are intrinsically unlike between type 1 (Sy1) and type 2 (Sy2) (Heckmann et al. 1989; Maiolino et al. 1995, 1997, 1998, 1999; Pérez-Olea & Colina 1996; Hunt et al. 1997; Malkan et al. 1998; Storchi-Bergmann & Schmitt 1998). Sy1's inhabit earlier type quiescent hosts, while Sy2's are frequently associated with circumnuclear starbursts, which often lie in barred galaxies. The observations may indicate that Sy2's are in an earlier evolutionary stage than Sy1's (Radovich et al. 1998), whereas in the unified model (Antonucci 1993, for a review) this dichotomy is simply accounted for with the orientation of the nucleus with an obscuring torus of subparsec scale. Second, the recent *HST* images of nearby QSOs have shown that luminous QSO phenomena occur preferentially in luminous host galaxies, often being ellipticals (McLeod & Rieke 1995b; Bahcall et al. 1997; Hooper et al. 1997). Also, at high redshifts, towards the QSO H1413+117 at $z = 2.546$ ("cloverleaf", a gravitationally lensed quasar) and QSO BR1202-0725 at $z = 4.69$, a large amount of dust have been detected, i.e., $\sim 10^9 M_\odot$ for H1413+117 and $\sim 10^8 M_\odot$ for BR1202-0725 (Barvainis et al. 1992; Omont et al. 1996). Molecular gas of at least $10^{11} M_\odot$ are also found for BR1202-0725 (Ohta et al. 1996a). These suggest that active star formation are on-going around the quasars. QSOs, however, are mostly identified as type 1 and only a few type 2 QSOs are discovered so far (Almaini et al. 1995; Ohta et al. 1996b; Brandt et al. 1997). Hence, a circumnuclear starburst does not seem to urge type 2 as far as quasars are concerned. QSOs are distinctive from Seyferts in that the host galaxy is in general fainter than the AGN itself (McLeod & Rieke 1995b; Bahcall et al. 1997; Hooper et al 1997). These facts on the host properties for Seyferts and QSOs suggest a possibility that the AGN type has a close relation to circumnuclear starburst events and the relative luminosity of starburst to the AGN.

We consider a physical mechanism which may connect circumnuclear star-forming activities with AGN type. Here, attention is concentrated on the radiative force by the circumnuclear starburst. In ultraluminous IR galaxies, the observed IR luminosities (Scoville et al. 1986; Soifer et al. 1986) are comparable to or greater than the Eddington luminosity for dust opacity (Umemura et al. 1998, 1999). Hence, the radiative force is very likely to play an important role on the circumnuclear structure of ~ 100 pc. In this Letter, supposing the mass distribution in circumnuclear regions, we analyze the equilibrium configuration and the stability of dusty gas which is supported by radiative force by a starburst and an AGN. In addition, taking the stellar evolution in the starburst regions into consideration, we investigate the time evolution of gas distributions, and attempt to relate the luminosity of the circumnuclear starburst to the evolution of the AGN type.

2. Radiatively-Supported Obscuring Wall

The circumnuclear starburst regions frequently exhibit ring-like features and have radial extension of ~ 10 pc up to kpc (Wilson et al. 1991; Forbes et al. 1994; Mauder et al. 1994; Buta et al. 1995; Barth et al. 1995; Maoz et al. 1996; Leitherer et al. 1996; Storchi-Bergman et al. 1996). Thus, here we consider a ring of starburst. (If the starburst regions are anisotropic or clumpy, the effects are expected to be smeared out as discussed later.) We calculate the radiation force and the gravity which are exerted on the dusty gas. Here, the gravitational potential is determined by four components, the galactic bulge, the central black hole, the gas disk, and the starburst ring. We assume the galactic bulge to be an uniform sphere whose mass and radius are $M_{\rm bul}$ and $R_{\rm bul}$, the mass of the central black hole to be $M_{\rm BH}$, the gas disk to be a Mestel disk whose mass and radius are $M_{\rm disk}$ and $R_{\rm disk}$, and the starburst ring to be an uniform torus whose mass, curvature radius, thickness, and bolometric luminosity are $M_{\rm SB}$, $R_{\rm SB}$, $a_{\rm SB}$, and $L_{\rm SB}$, respectively (see Figure 1). The observations of IRAS galaxies by Scoville et al. (1991) show that the central regions within several hundred parsecs possess the gas of $\lesssim 10^{10} {\rm M}_\odot$. By taking this fact into account, we adopt the mass ratio as $M_{\rm bul} : M_{\rm BH} : M_{\rm disk} : M_{\rm SB} = 1 : 0.01 : 0.1 : 1$. Also, it is found that the starburst ring often consists of compact star clusters of $\lesssim 10$ pc (Barth et al.

1995; Maoz et al. 1996; Leitherer et al. 1996). The size of these clusters is about a tenth of radial extension of the starburst ring. Therefore, we assume $R_{\rm bul} : R_{\rm disk} : R_{\rm SB} : a_{\rm SB} = 10 : 1 : 1 : 0.1$. In addition, the nucleus is postulated to be a point source whose bolometric luminosity is $L_{\rm nuc}$.

Here, the material is assumed to be subject to the radiative force directly by the starburst radiation. The radiation flux by an infinitesimal volume element, dV, of the starburst ring is given by $dF^i(r,z) = (\rho_{\rm SB}/4\pi l^2)n^i dV$, at a point of (r,z) in cylindrical coordinates, where i denotes r or z, $\rho_{\rm SB}$ $(= L_{\rm SB}/2\pi^2 a_{\rm SB}^2 R_{\rm SB})$ is the luminosity density of the starburst ring, l is the distance from (r,z) to this element, and n^i is a directional cosine. Hence, the radiation flux force by the starburst ring and the nucleus at (r,z) is given by

$$f^i_{\rm rad} = \frac{\chi}{c}\int \frac{\rho_{\rm SB}}{4\pi l^2} n^i dV + \frac{\chi}{c}\frac{iL_{\rm nuc}}{4\pi\left(r^2+z^2\right)^{3/2}}, \tag{1}$$

where χ is the mass extinction coefficient for the dusty gas (Umemura et al. 1998) and c is the light speed. Using the above equation, the equilibrium between the radiation force and the gravity is written as

$$f^z_{\rm rad} + f^z_{\rm grav} = 0, \tag{2}$$

in the vertical directions and

$$\frac{j^3}{r^2} + f^r_{\rm rad} + f^r_{\rm grav} = 0, \tag{3}$$

in the radial directions, where j is the specific angular momentum of the dusty gas and $f^i_{\rm grav}$ is the gravitational force.

In figure 2, in the case that the starburst ring is a dominant radiation source (Case A), the resultant equilibrium branches are shown in the r-z space. Here, $\Gamma_{\rm SB}$ and $\Gamma_{\rm nuc}$ are the Eddington measures defined by $\Gamma_{\rm SB} = L_{\rm SB}/(4\pi cGM_{\rm total}/\chi)$ and $\Gamma_{\rm nuc} = L_{\rm nuc}/(4\pi cGM_{\rm total}/\chi)$ respectively with $M_{\rm total} = M_{\rm bul} + M_{\rm BH} + M_{\rm disk} + M_{\rm SB}$. The solid and dashed curves represent the equilibrium branches which are stable in vertical directions. Above the curves, the vertical component of the gravity which works to lower the gas is stronger than the radiation force, while below the curves the radiation force lifts the gas towards the curves. The dotted curves show the vertically unstable branches. The gas is accelerated upwards by the radiative force above the curves or falls downwards by the gravity below the curves.

In order to get the configuration of finally stable equilibrium, the stability in radial directions must be taken also into consideration. On the dashed curves, the effective potential in the radial directions turns out to be locally maximal. Thus, the dashed branches are unstable points of saddle type. Finally, only solid curves are stable branches. Figure 2 shows that stable branches emerge only for $\Gamma_{\rm SB} \le 1$. This agrees with a naive expectation. If $\Gamma_{\rm SB} > 1$, the radiation force blows out the dusty gas in most regions. (e.g. see a dotted curve of $\Gamma_{\rm SB} = 2$). When $\Gamma_{\rm SB} \le 1$, the covering factor of the stable wall is a function of $\Gamma_{\rm SB}$. If $\Gamma_{\rm SB} \sim 1$, the wall surrounds both the nucleus and the starburst ring. When the starburst luminosity is smaller than $\Gamma_{\rm SB} = 0.55$, the wall forms only in the vicinity of the starburst ring and exhibits a torus-like configuration. The A_V of the wall is expected to be at least several, because radiative force directly from a starburst can be exerted on such a wall. Then, this large-scale wall of dusty gas would work obscure the nucleus. When the flux force of scattered diffuse radiation operates efficiently in the wall, the wall of larger optical depth may be supported and therefore A_V could be much larger. (The detail should be investigated by multi-dimensional radiation hydrodynamics, which will be performed in the future analysis.) If A_V of the wall is only several magnitudes, the AGN would be changed to an intermediate type between type 1 and 2, e.g. type 1.3, 1.5 and so on, while the A_V greater than ten magnitudes would result in the perfect shift from type 1 to type 2.

Next, we examine the case that the nucleus is brighter than the circumnuclear starburst (Case B). In this case, only vertically stable branches emerge even if $\Gamma_{\rm SB} + \Gamma_{\rm nuc} < 1$ (see Fig. 3). On the dashed curves in Fig. 3, contrastively to the Case A, there is no solution for the radial equilibrium, regardless of the value of starburst luminosity. The gas around the dashed curves is swung away due to the cooperation of radiative force and angular momentum. Resultantly, the formation of the stable wall is precluded in the Case B. This implies that the luminous nuclei like QSOs are not likely to be obscured, which are therefore mostly identified as type 1.

Further, for the Case A, we consider the effects of stellar evolution in the starburst regions on the stable equilibrium branches. We assume a Salpeter-type initial mass function (IMF), $\phi = A(m_*/M_\odot)^{-1.35}$, the mass-luminosity relation, $(l_*/L_\odot) = (m_*/M_\odot)^{3.7}$, and the mass-age relation, $\tau = 1.1 \times 10^{10}{\rm yr}(m_*/M_\odot)^{-2.7}$, where m_* and l_* are respectively the stellar mass and luminosity. Recently, it has been revealed that in starburst regions the IMF is deficient in low-mass stars, with the cutoff of about $2M_\odot$, and the upper mass limit is inferred to be around $40M_\odot$ (Doyon et al. 1992; Charlot et al. 1993; Doane & Mathews 1993; Hill et al. 1994; Brandl et al. 1996). Using the IMF for a mass range of $[2M_\odot, 40M_\odot]$ and the above relations, the total stellar luminosity of starburst regions is given by a function of time as $L_* = 1.5 \times 10^{10}\left(87t_7^{-0.87} - 1\right)(M_{SB}/10^{10}M_\odot)\,L_\odot$, where t_7 is the elapsed time after the coeval starburst in units of 10^7yr. Also, if we postulate that stars of $> 8M_\odot$ are destined to undergo supernova explosions and release the energy radiatively with the efficiency of ε to the rest mass energy, the total supernova luminosity is $L_{\rm SN} = 1.7 \times 10^{11} t_7^{-0.87}(M_{\rm SB}/10^{10}M_\odot)(\varepsilon/10^{-4})\,L_\odot$ until $t_7 = 4.0$ and $L_{\rm SN} = 0$ when $t_7 > 4.0$. Hence, the total luminosity of the starburst ring is given by

$$L_{\rm SB}(t_7) = L_* + L_{\rm SN}. \tag{4}$$

Using this dependence on time, the luminosity can be translated into the age of the starburst regions. Therefore, the values of $\Gamma_{\rm SB}$ in figure 2 represent the evolutionary stage of the circumnuclear starburst. For instance, if we adopt $M_{\rm SB} = 10^{10}M_\odot$, $\Gamma_{\rm SB} = 1$ and 0.55 correspond to 4.2×10^7yr and 8.1×10^7yr, respectively.

To summarize, if $\Gamma_{\rm SB} > 1$ in the early evolutionary stage, the dusty gas is blown away by radiative acceleration. Since the blown-out dusty gas would emit the strong IR radiation, we may recognize the objects as ultraluminous infrared galaxies. When $\Gamma_{\rm SB}$ becomes just below unity, both the nucleus and the starburst ring are surrounded by the dusty wall. Then, the AGN is likely to be type 2. In the later stages, the dusty gas forms a torus-like obscuring wall, which shrinks on a time-scale of several 10^7 yr. Then, the AGN tends to be identified as type 1 for a wide viewing angle. This implies that the type of AGN evolves from higher to lower in several 10^7 yr according as the circumnuclear starburst becomes dimmer.

3. Discussion

Here, we have assumed that the nuclear activity and the circumnuclear starburst are the simultaneous events. A solution, for instance, which links the two events, is the radiatively-driven mass accretion onto a central black hole due to the radiation drag (Umemura et al. 1997, 1998; Ohsuga et al. 1999). However, in very early luminous phases of the starburst, the mass accretion onto the black hole is prevented due to the super-Eddington radiative force. It result in a radiative blizzard in nuclear regions. Thus, the nucleus is just identified as an ultraluminous infrared galaxy without being accompanied by an AGN. We predict in the present model that ultraluminous infrared galaxies evolve into Seyferts or QSOs in later less luminous phases of the starburst.

The circumnuclear starburst could not be axisymmetric but clumpy. However, the rotational time scale of the starburst ring is shorter than the shrinking time-scale of the obscuring wall. In the present case, the former is around 3.0×10^6yr and the latter is several 10^7yr. Therefore, the anisotropies of the starburst are expected to be smeared out by a 'wheel effect'. The stable obscuring wall might be subject to the other local instabilities, i.e., Rayleigh-Taylor or self-gravitational instabilities. The density gradient of the dusty wall is positive inside the equilibrium surface and negative outside the surface. They are in the same directions as the effective acceleration. Thus, the wall would not be subject to Rayleigh-Taylor instabilities. As for the self-gravitational instability, the time-scale of the instability could be as short as $\lesssim 10^6$ yr. So, the wall may fragment on a time-scale shorter than the evolutionary time-scale of the wall. Then, numerous compact gas clouds would form in the wall. They would emit the narrow emission lines because they have the velocity dispersion of several 100 km s^{-1}. Also, if the compact clouds are optically thick, the radiative force is less effective for them, so that they fall into the central regions. They also may partially obscure the nucleus.

In this letter, we do not argue that a conventional obscuring torus of subparsec scale is dispensable. Even if the inner obscuring torus may operate to intrinsically differentiate the type of AGNs, the present large-scale wall can work also to raise further the type index. In particular, the present mechanism may provide a physical solution to account for the tendency that Sy2's are more frequently associated with circumnuclear starbursts than Sy1's, whereas quasars are mostly observed as type 1 regardless of star-forming activity in the host galaxies. If we adopt the size and mass that conform to realistic values, e.g., $R_{\rm SB} \sim 100$ pc and $M_{\rm SB} \sim 10^{10} M_{\odot}$, the obscuring wall is extended to several 100 pc. Interestingly, it is recently reported that the spectra of a sample of AGNs are more consistent with obscuring material extended up to $\gtrsim$ 100 pc around the nuclei (Rudy et al. 1988; Miller et al. 1991; Scarrott et al. 1991; Goodrich 1995; McLeod & Rieke 1995a; Maiolino et al. 1995; Maiolino & Rieke 1995) and the hosts of Sy'2 possess more frequently extended dust lanes (Malkan et al. 1998). Also, the covering factor of a dusty torus around a QSO, MG 0414+0534, is fairly small (Oya et al. 1999). These observations are quite intriguing in the light of the present picture.

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REFERENCES

Almaini, O., et al. 1995, MNRAS, 277, L31

Antonucci, R. R. J. 1993, ARA&A, 30, 705

Bahcall, J. N., Kirhakos, S., & Saxe, D. H. 1997, ApJ, 479, 642

Barth, A. J., Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1995, AJ, 110, 1009

Barvainis, R., Antonucci, R., & Coleman, P. 1992, ApJ, 399, L19

Brandl, B., et al. 1996, ApJ, 466, 254

Brandt, W. N., et al. 1997, MNRAS, 290, 617

Buta, R., Purcell, G. B., & Crocker, D. A. 1995, AJ, 110, 1588

Charlot, S., Ferrari, F., Mathews, G. J., & Silk, J. 1993, ApJ, 419, L57

Doane, J. S., & Mathews, W. G. 1993, ApJ, 419, 573

Doyon, R., Puxley, P. J., & Joseph, R. D. 1992, ApJ, 397, 117

Forbes, D. A., Norris, R. P., Williger, G. M., & Smith, R. C. 1994, AJ, 107, 984

Goodrich, R. W. 1995, ApJ, 440, 141

Heckman, T. M., Blitz, L., Wilson, A. S., Armus, L., & Miley, G. K. 1989, ApJ, 342, 735

Hill, J. K., et al. 1994, ApJ, 425, 122

Hooper, E. J., Impey, C. D., & Foltz, C. B. 1997, ApJ, 480, L95

Hunt, L. K., et al. 1997, ApJS, 108, 229

Leitherer, C., et al. 1996, ApJ, 465, 717

Maiolino, R., Ruiz, M., Rieke, G. H., & Keller, L. D. 1995, ApJ, 446, 561

Maiolino, R. & Rieke, G. H. 1995, ApJ, 454, 95

Maiolino, R., Ruiz, M., Rieke, G. H., & Papadopoulos, P. 1997, ApJ, 485, 552

Maiolino, R., Krabbe, Thatte, N., & Genzel, R. 1998, ApJ, 493, 650

Maiolino, R., Risaliti, G., & Salvati, M. 1999, A&A, 341, L35

Malkan, M. A., Gorjian, V., & Tam, R. 1998, ApJS, 117, 25

Maoz, D., et al. 1996, AJ, 111, 2248

Mauder, W., Weigelt, G., Appenzeller, I., & Wagner, S. J. 1994, A&A, 285, 44

McLeod, K. K. & Rieke, G. H. 1995a, ApJ, 441, 96

McLeod, K. K., & Rieke, G. H. 1995b, ApJ, 454, L77

Miller, J. S., Goodrich, R. W., & Mathews, W. G. 1991, ApJ, 378, 47

Ohsuga, K., Umemura, M., Fukue, J., & Mineshige, S. 1999, PASJ, in press

Ohta, K., et al. 1996a, Nature, 382, 426

Ohta, K., et al. 1996b, ApJ, 458, L57

Omont, A., et al. 1996, Nature, 382, 428

Oya, S., Iwai, J., Iwamuro, F., & Maihara, T. 1999, in The Universe as seen by ISO, October 20-23 1998 in Paris, a contribution paper

Pérez-Olea, D. E. & Colina, L. 1996, ApJ, 468, 191

Radovich, M., Rafanelli, P., & Barbon, R. 1998, A&A, 334, 124

Rudy, R. J., Cohen, R. D., & Ake, T. B. 1988, ApJ, 332, 172

Scarrott, S. M., Rolph, C. D., Wolstencroft, R. W., & Tadhunter, C. N. 1991, MNRAS, 249, 16p

Scoville, N. Z., et al. 1986, ApJ, 311, L47

Scoville, N. Z., Sargent, A. I., Sanders, D. B., & Soifer, B. T. 1991, ApJ, 366, L5

Soifer, B. T., et al. 1986, ApJ, 303, L41

Storchi-Bergmann, T., Wilson, A. S., & Baldmin, J. A. 1996, ApJ, 460, 252

Storchi-Bergmann, T. & Schmitt, H. R. 1998, preprint (astro-ph/9812017)

Umemura, M., Fukue, J., & Mineshige, S. 1997, ApJ, 479, L97

Umemura, M., Fukue, J., & Mineshige, S. 1998, MNRAS, 229, 1123

Umemura, M., Fukue, J., & Mineshige, S. 1999, Advances in Space Research, in press

Wilson, A. S., Helfer, T. T., Haniff, C. A., & Ward, M. J. 1991, ApJ, 381, 79

This preprint was prepared with the AAS LaTeX macros v4.0.

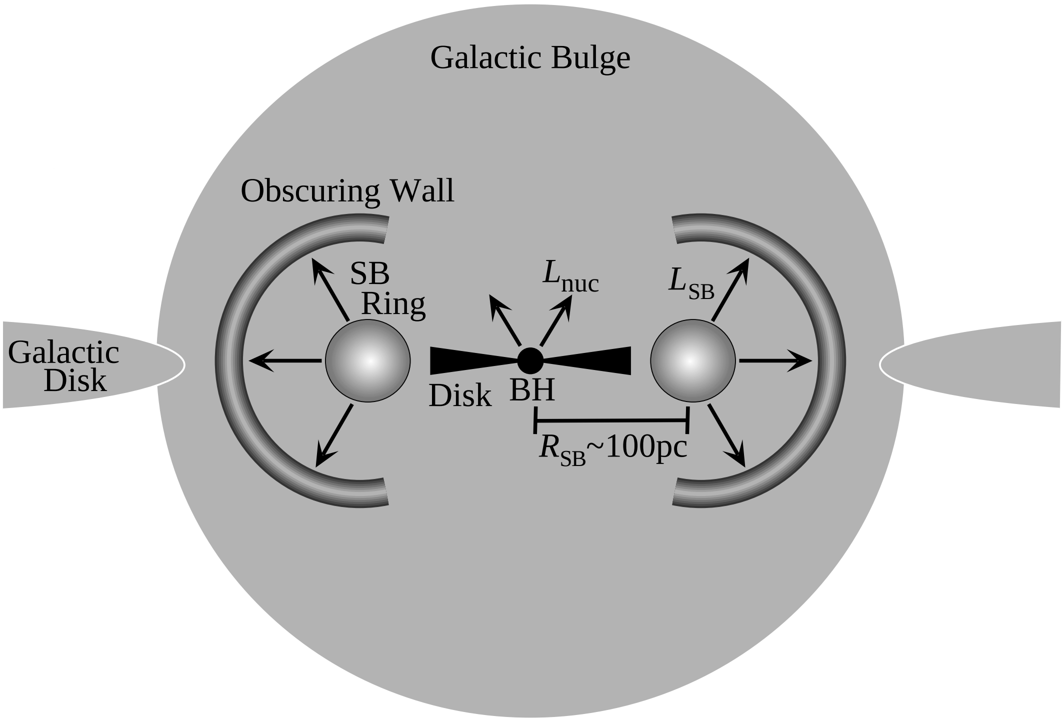

Fig. 1.— A schematic edge-on view of the circumnuclear structure in the present picture. Here, we assume two components of radiation sources, an AGN (luminosity $L_{\rm nuc}$) and a starburst ring (luminosity $L_{\rm SB}$). The gravitational fields are modeled by four-component gravity sources, i.e., a central black hole, a gas disk, a starburst ring, and a galactic bulge. The typical size of the starburst ring is around 100 pc, so that an obscuring wall of several 100 pc is built up due to the intensive radiation force by the starburst ring.

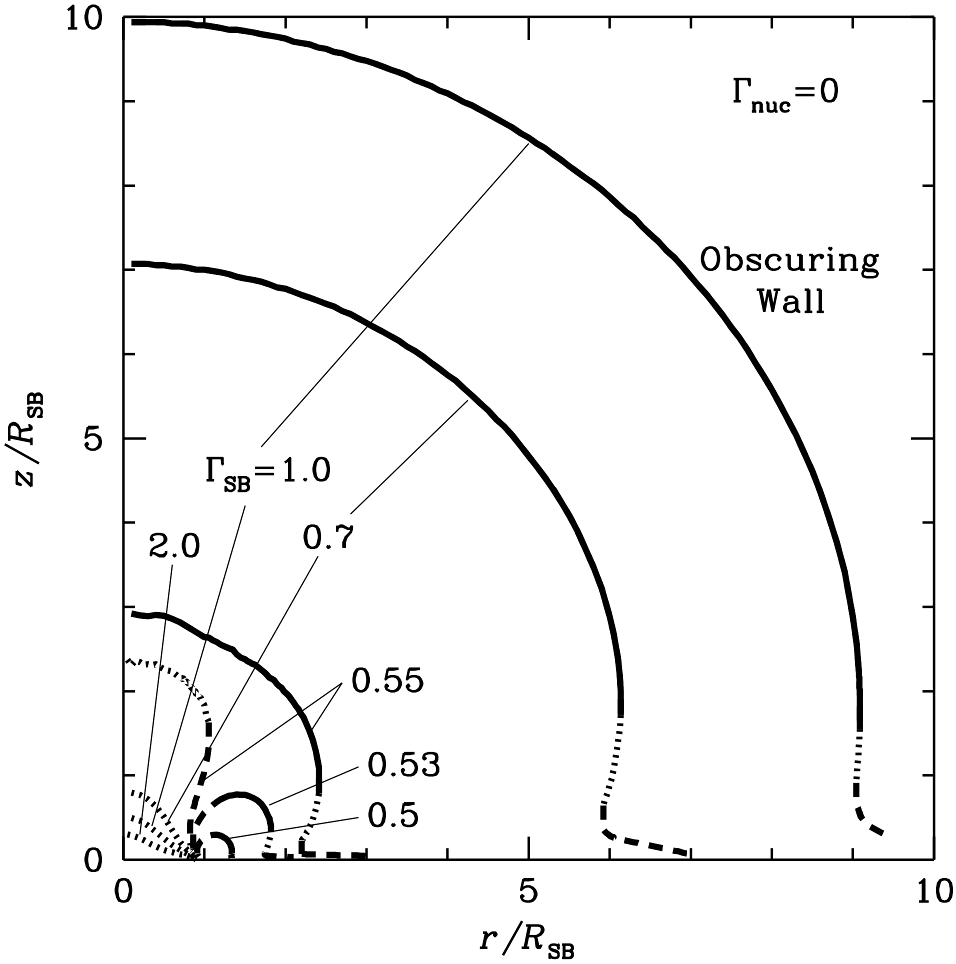

Fig. 2.— Equilibrium configuration of dusty gas on which the radiation force and gravity are exerted is shown in r-z space for a wide variety of $\Gamma_{\rm SB}$. The r and z are normalized by the starburst ring radius, $R_{\rm SB}$. Here, the nuclear luminosity is assumed to be null. The solid and dashed curves represent vertically stable branches, while the dotted curved are vertically unstable branches. Further, on the dashed curves the *radial* effective potential is locally maximal, and therefore they are unstable points of saddle type, while the solid curves are stable radially as well as vertically. The solid curves show the final configuration of the stable obscuring wall.

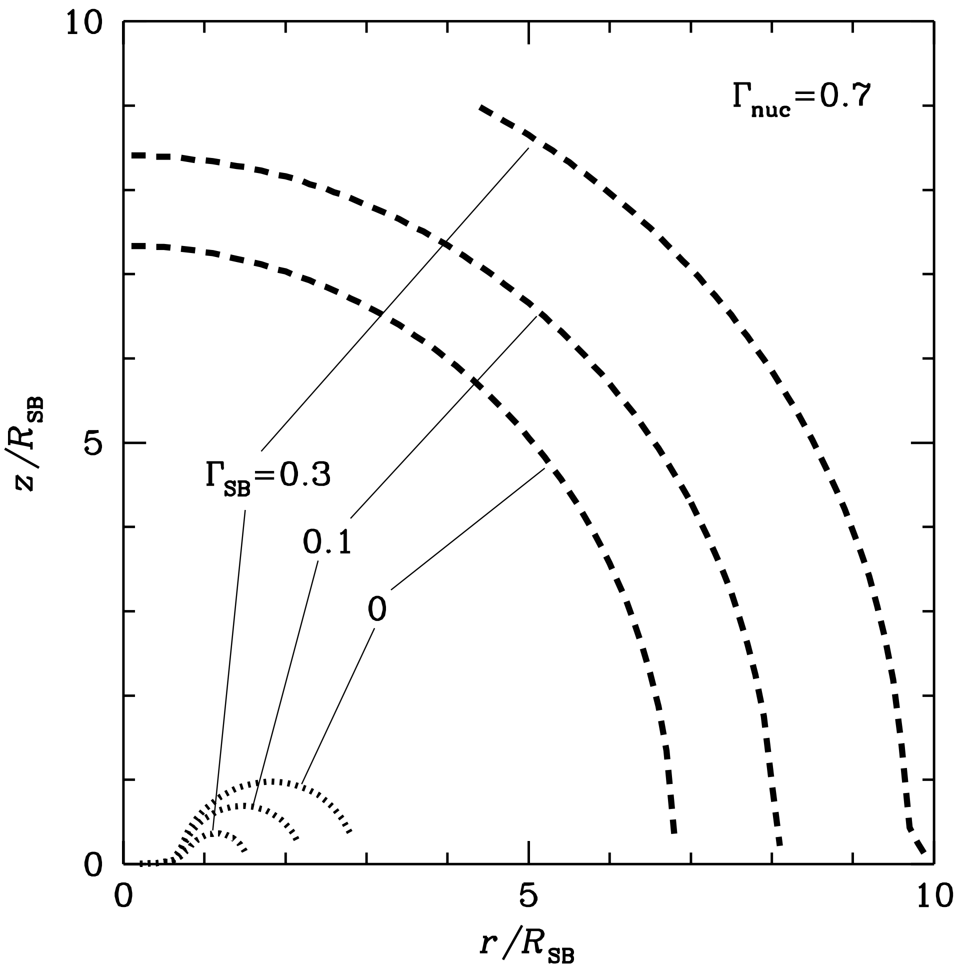

Fig. 3.— Same as Figure 2, but for a high nucleus luminosity ($\Gamma_{\rm nuc} = 0.7$). In this case, all the vertically stable branches do not satisfy the radial equilibrium, regardless of starburst activity. Hence, no stable wall forms.